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ARTIFICIAL INTELLIGENCE IN DENTISTRY: CLINICAL APPLICATIONS, LIMITATIONS, AND FUTURE PERSPECTIVES

INTELIGÊNCIA ARTIFICIAL NA ODONTOLOGIA: APLICAÇÕES CLÍNICAS, LIMITAÇÕES E PERSPECTIVAS FUTURAS

INTELIGENCIA ARTIFICIAL EN ODONTOLOGÍA: APLICACIONES CLÍNICAS, LIMITACIONES Y PERSPECTIVAS FUTURAS

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ABSTRACT

Objective: To critically evaluate the current clinical applications of artificial intelligence (AI) in dentistry, as well as its limitations and future perspectives across different dental specialties.

Methodology: A narrative review was conducted through a comprehensive search of electronic databases, including PubMed, Scopus, and Google Scholar. Relevant studies published in English were selected based on their focus on AI applications in dentistry, including diagnostics, treatment planning, and outcome prediction. Articles were screened for relevance, and key findings were qualitatively synthesized.

Results: AI has demonstrated significant potential in multiple areas of dentistry, particularly in radiographic interpretation, caries detection, periodontal assessment, orthodontic planning, and oral pathology screening. Machine learning and deep learning models have shown high diagnostic accuracy, often comparable to or exceeding that of clinicians. However, important limitations persist, including data heterogeneity, lack of standardized datasets, limited external validation, and ethical concerns related to data privacy and

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algorithm transparency. Additionally, integration into routine clinical workflows remains challenging.

Conclusion: AI represents a transformative tool in modern dentistry, with the potential to enhance diagnostic precision and clinical decision-making. Despite promising advancements, its widespread adoption requires further validation, regulatory frameworks, and clinician training. Future research should focus on improving model generalizability, addressing ethical concerns, and ensuring seamless clinical integration.

Keywords: Artificial Intelligence. Dentistry. Machine Learning. Deep Learning. Diagnostic Imaging. Clinical Decision-Making. Digital Dentistry. Predictive Analytics.

RESUMO

Objetivo: Avaliar criticamente as aplicações clínicas atuais da inteligência artificial (IA) na odontologia, bem como suas limitações e perspectivas futuras em diferentes especialidades odontológicas.

Metodologia: Foi realizada uma revisão narrativa por meio de uma busca abrangente em bases de dados eletrônicas, incluindo PubMed, Scopus e Google Scholar. Estudos relevantes publicados em inglês foram selecionados com base em seu foco nas aplicações de IA na odontologia, incluindo diagnóstico, planejamento de tratamento e predição de resultados. Os artigos foram triados quanto à relevância, e os principais achados foram sintetizados qualitativamente.

Resultados: A IA demonstrou potencial significativo em diversas áreas da odontologia, particularmente na interpretação radiográfica, detecção de cáries, avaliação periodontal, planejamento ortodôntico e triagem de patologias orais. Modelos de machine learning e deep learning apresentaram alta precisão diagnóstica, frequentemente comparável ou superior à de clínicos. No entanto, persistem limitações importantes, incluindo heterogeneidade de dados, falta de conjuntos de dados padronizados, validação externa limitada e preocupações éticas relacionadas à privacidade de dados e transparência de algoritmos. Além disso, a integração aos fluxos de trabalho clínicos rotineiros ainda representa um desafio.

Conclusão: A IA representa uma ferramenta transformadora na odontologia moderna, com potencial para melhorar a precisão diagnóstica e a tomada de decisões clínicas. Apesar dos avanços promissores, sua adoção generalizada exige validação adicional, estruturas regulatórias e treinamento de clínicos. Pesquisas futuras devem focar na melhoria da generalização dos modelos, abordagem das questões éticas e garantia de integração clínica eficiente.

Palavras-chave: Inteligência Artificial. Odontologia. Machine Learning. Deep Learning. Imagem Diagnóstica. Tomada de Decisão Clínica. Odontologia Digital. Análise Preditiva.

RESUMEN

Objetivo: Evaluar críticamente las aplicaciones clínicas actuales de la inteligencia artificial (IA) en odontología, así como sus limitaciones y perspectivas futuras en diferentes especialidades odontológicas.

Metodología: Se realizó una revisión narrativa mediante una búsqueda exhaustiva en bases de datos electrónicas, incluyendo PubMed, Scopus y Google Scholar. Se seleccionaron

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estudios relevantes publicados en inglés, en función de su enfoque en aplicaciones de IA en odontología, incluyendo diagnóstico, planificación del tratamiento y predicción de resultados. Los artículos fueron evaluados por su relevancia, y los hallazgos clave se sintetizaron cualitativamente.

Resultados: La IA ha demostrado un potencial significativo en múltiples áreas de la odontología, particularmente en la interpretación radiográfica, detección de caries, evaluación periodontal, planificación ortodóntica y cribado de patologías orales. Los modelos de machine learning y deep learning han mostrado alta precisión diagnóstica, a menudo comparable o superior a la de los clínicos. Sin embargo, persisten limitaciones importantes, incluyendo heterogeneidad de datos, falta de conjuntos de datos estandarizados, validación externa limitada y preocupaciones éticas relacionadas con la privacidad de los datos y la transparencia de los algoritmos. Además, la integración en los flujos de trabajo clínicos rutinarios sigue siendo un desafío.

Conclusión: La IA representa una herramienta transformadora en la odontología moderna, con potencial para mejorar la precisión diagnóstica y la toma de decisiones clínicas. A pesar de los avances prometedores, su adopción generalizada requiere validación adicional, marcos regulatorios y capacitación de los clínicos. La investigación futura debe centrarse en mejorar la generalización de los modelos, abordar las preocupaciones éticas y asegurar una integración clínica eficiente.

Palabras clave: Inteligencia Artificial. Odontología. Machine Learning. Deep Learning. Imagen Diagnóstica. Toma de Decisiones Clínicas. Odontología Digital. Análisis Predictivo.

1 INTRODUCTION

Artificial intelligence (AI) has undergone a remarkable transformation over recent decades, evolving from a largely theoretical domain within computer science into a central pillar of innovation across multiple sectors, particularly in healthcare. Broadly defined, AI refers to computational systems capable of performing tasks that typically require human intelligence, including learning, reasoning, pattern recognition, and decision-making. Within this framework, subfields such as machine learning (ML) and deep learning (DL) have gained prominence due to their ability to process large datasets and identify complex, non-linear relationships that may not be readily apparent through conventional analytical methods (Topol, 2019; Russell & Norvig, 2021). In medicine, AI has already demonstrated transformative potential in areas such as radiology, dermatology, and oncology, where image-based diagnostics and large-scale data interpretation are fundamental. Notably, deep learning algorithms particularly convolutional neural networks (CNNs) have shown performance comparable to, and in some cases exceeding, that of human experts in diagnostic tasks (Esteva et al., 2017; Litjens et al., 2017). Dentistry, as a discipline that heavily relies on visual assessment, radiographic interpretation, and increasingly digital workflows, represents a highly suitable environment for the integration of AI technologies (Schwendicke et al., 2020).

The rapid digitalization of dental practice has played a crucial role in enabling the adoption of AI. The widespread use of cone-beam computed tomography (CBCT), digital radiography, intraoral scanning, and electronic health records has resulted in the generation of vast amounts of structured and unstructured data. These datasets provide the necessary substrate for training AI models capable of performing diagnostic and predictive tasks. In particular, CNN-based systems have demonstrated high accuracy in detecting dental caries, periapical lesions, periodontal bone loss, and other oral pathologies using radiographic images (Lee et al., 2018; Kühnisch et al., 2020). Such developments are especially relevant in addressing issues of diagnostic variability among clinicians, as AI has the potential to standardize interpretations and reduce subjectivity in clinical decision-making.

Beyond diagnostics, AI applications in dentistry are expanding into treatment planning, prognostic assessment, and workflow optimization. In orthodontics, automated cephalometric landmark detection and treatment simulations have significantly reduced manual workload and improved reproducibility (Kunz et al., 2020). In implant dentistry, AI-driven planning systems can assist clinicians in evaluating bone quality, optimizing implant positioning, and predicting treatment outcomes. Similarly, in prosthodontics and restorative dentistry, AI tools are being developed to enhance digital smile design and CAD/CAM processes. These

advancements align closely with the broader concept of precision dentistry, which emphasizes individualized treatment planning based on patient-specific data (Schwendicke et al., 2020; Meskó & Görög, 2020). Another important dimension of AI in dentistry is its potential role in preventive care and public health. Predictive models based on patient data, including demographic, behavioral, and clinical variables can be used to assess caries risk, periodontal disease progression, and treatment outcomes. Such tools may enable earlier interventions and more efficient allocation of healthcare resources. Additionally, AI-powered teledentistry platforms have the potential to expand access to care, particularly in underserved populations, by facilitating remote diagnosis and consultation (Meskó & Görög, 2020).

Despite these promising applications, the implementation of AI in dentistry is not without significant challenges. One of the primary limitations relates to data quality and representativeness. AI models are highly dependent on the datasets used for training, and biases within these datasets can lead to skewed or unreliable outputs. Many studies rely on relatively small, homogeneous, or highly curated datasets, which may not reflect the diversity encountered in real-world clinical settings. Consequently, the generalizability of these models remains a major concern (Kelly et al., 2019). Furthermore, the “black box” nature of many deep learning algorithms poses challenges in terms of interpretability and transparency. Unlike traditional statistical models, which often provide clear relationships between variables, deep learning systems may produce highly accurate predictions without offering insight into the underlying decision-making process. This lack of explainability can hinder clinical trust and raises important ethical and legal questions regarding accountability and informed consent (Topol, 2019; Kelly et al., 2019).

Ethical considerations extend beyond algorithm transparency to include issues such as data privacy, security, and ownership. The use of patient data for training AI systems requires strict adherence to regulatory frameworks and ethical guidelines to ensure confidentiality and prevent misuse. Moreover, the integration of AI into clinical practice raises questions about the role of the clinician, particularly in cases where AI-generated recommendations conflict with clinical judgment. Rather than replacing clinicians, AI is more appropriately viewed as a decision-support tool; however, defining the boundaries of responsibility remains an ongoing challenge (Meskó & Görög, 2020).

Another critical barrier to the widespread adoption of AI in dentistry is the lack of standardized evaluation protocols and regulatory oversight. While numerous studies report high levels of accuracy for AI models, these results are often obtained under controlled experimental conditions and may not translate directly to clinical practice. There is a pressing

need for prospective clinical trials, external validation studies, and standardized reporting guidelines to ensure the reliability and reproducibility of AI-based tools (Schwendicke et al., 2020). Additionally, regulatory bodies must establish clear frameworks for the approval and monitoring of AI technologies in healthcare.

The successful integration of AI into dentistry also depends on the readiness of the dental workforce. Many clinicians may lack familiarity with AI technologies, which can limit their ability to effectively interpret and utilize AI-generated outputs. Therefore, incorporating digital literacy and AI-related competencies into dental education and continuing professional development is essential. Without adequate training, there is a risk that AI tools may be underutilized or misapplied, ultimately limiting their clinical impact. Given the rapid expansion of AI research in dentistry and the complexity of its clinical, ethical, and technological implications, a comprehensive and critical synthesis of the available evidence is both timely and necessary. While numerous studies have highlighted the potential benefits of AI, there remains a need to balance enthusiasm with a realistic assessment of its limitations.

In this context, the present narrative review aims to provide a comprehensive overview of the current applications of AI in dentistry, critically evaluate its limitations, and explore future directions for research and clinical integration. By addressing both the opportunities and challenges associated with AI, this review seeks to contribute to a more nuanced understanding of its role in shaping the future of dental practice.

2 METHODOLOGY

This narrative review was conducted to synthesize current evidence on the applications of artificial intelligence in dentistry. A comprehensive literature search was performed in electronic databases, including PubMed (MEDLINE), Scopus, and Google Scholar, covering studies published up to 2025. The search strategy combined controlled vocabulary and free-text terms such as “artificial intelligence,” “machine learning,” “deep learning,” and “dentistry.”

Eligible studies included original research articles, clinical studies, and relevant reviews addressing AI applications in dental diagnostics, treatment planning, and outcome prediction. Articles not available in English or not directly related to clinical dentistry were excluded

The selection of studies was based on relevance to the topic and conceptual contribution rather than strict methodological criteria, as expected in narrative reviews. Data were qualitatively synthesized, focusing on major clinical domains, technological approaches,

reported performance, and identified limitations. No formal risk of bias assessment or meta-analysis was performed.

3 RESULTS

3.1 CLINICAL APPLICATIONS OF ARTIFICIAL INTELLIGENCE IN DENTISTRY

The analysis of the selected literature reveals that artificial intelligence (AI) has demonstrated consistent applicability across multiple dental specialties, with the strongest evidence observed in diagnostic imaging and radiology, followed by orthodontics, oral pathology, and clinical workflow optimization.

3.1.1 Radiology and Diagnostic Imaging

Radiology represents the most advanced and evidence-supported application of AI in dentistry. Deep learning models, particularly convolutional neural networks (CNNs), have been extensively trained to detect dental caries, periapical lesions, periodontal bone loss, and anatomical structures using radiographic data. A landmark study by J. H. Lee et al. (2018) demonstrated that a CNN-based system achieved high diagnostic performance in detecting dental caries on periapical radiographs, with sensitivity and specificity comparable to experienced clinicians. Similarly, Falk Schwendicke et al. (2020) reported that AI systems can reach diagnostic performance levels similar to or even exceeding those of human experts under controlled conditions.

More recent evidence from H. Ding et al. (2023) confirms that AI models consistently achieve high accuracy in radiographic interpretation, particularly when trained on large annotated datasets. Importantly, these studies emphasize that AI reduces inter- and intra-observer variability, contributing to more standardized diagnostic outcomes. However, despite high reported accuracy, most studies are based on retrospective datasets, and real-world clinical validation remains limited (Schwendicke et al., 2020; Ding et al., 2023).

3.1.2 Orthodontics and Dentofacial Orthopedics

In orthodontics, AI applications are primarily focused on cephalometric analysis, treatment planning, and outcome prediction.

According to Kunz et al. (2020), machine learning algorithms can automatically identify cephalometric landmarks with high precision, significantly reducing manual workload and increasing reproducibility. Furthermore, AI-based models have been used to simulate orthodontic treatment outcomes and predict tooth movement dynamics. A particularly relevant advancement is the integration of AI into orthognathic surgery planning, where predictive

systems generate simulated postoperative facial profiles. These simulations enhance clinician–patient communication and support more accurate expectation management (Meskó & Görög, 2020; Ding et al., 2023).

3.1.3 Oral Pathology and Disease Detection

AI has shown strong potential in oral pathology, particularly in the early detection of oral cancer and potentially malignant disorders.

Deep learning models trained on photographic and histopathological images can identify lesion characteristics and assist in differential diagnosis. According to Ding et al. (2023), AI systems have demonstrated high accuracy in detecting oral squamous cell carcinoma from clinical images, suggesting their utility as screening tools.

Additionally, N. H. Wood (2022) highlights that AI-driven diagnostic systems can be integrated into teledentistry platforms, allowing remote screening and triaging of patients, particularly in underserved populations.

3.1.4 Periodontology and Preventive Dentistry

In periodontology, AI has been applied to assess periodontal bone loss and predict disease progression using both radiographic and clinical data.

Schwendicke et al. (2020) emphasize that machine learning models can identify complex patterns associated with periodontal disease, supporting personalized risk assessment and early intervention strategies. Similarly, Ding et al. (2023) report that predictive models incorporating behavioral and clinical variables can estimate disease progression and treatment outcomes.

These findings suggest that AI may play a central role in the shift toward precision dentistry and preventive care.

3.1.5 Clinical Workflow Optimization and Patient Management

AI is increasingly being incorporated into non-clinical aspects of dentistry, particularly in practice management and patient communication.

According to Meskó and Görög (2020), AI-based systems can automate administrative tasks such as appointment scheduling, patient reminders, and digital communication. These tools improve efficiency and reduce the workload of dental professionals. Furthermore, AI can generate educational materials, including visual explanations of procedures and treatment plans, enhancing patient understanding and adherence (Wood, 2022).

3.2 APPLICATIONS OF ARTIFICIAL INTELLIGENCE IN DENTAL EDUCATION

AI has also emerged as a powerful tool in dental education, supporting both teaching and research activities.

According to Russell and Norvig (2021), AI systems are capable of assisting in knowledge organization, content generation, and decision support. In dentistry, these tools can be used to generate educational materials, summarize scientific literature, and support research development.

Ding et al. (2023) highlight that AI can enhance learning by providing adaptive and personalized educational experiences. Additionally, AI-generated visual content, including anatomical diagrams and clinical simulations, has improved the quality of teaching resources.

However, concerns regarding overreliance on AI and potential impacts on critical thinking and academic integrity have been raised (Kelly et al., 2019).

4 DISCUSSION

Artificial intelligence is no longer a speculative innovation in dentistry; it is rapidly becoming a structural component of modern clinical practice. The findings of this review demonstrate that AI has already achieved clinically relevant performance in multiple domains, particularly in diagnostic imaging, where its ability to process large volumes of data with consistency and speed represents a clear advantage over traditional methods.

One of the most significant contributions of AI lies in its capacity to reduce diagnostic variability. Dentistry, by nature, involves a degree of subjectivity, especially in radiographic interpretation and clinical decision-making. AI systems, when properly trained, introduce a level of standardization that can minimize human-related inconsistencies. This does not eliminate the role of the clinician but instead redefines it shifting from sole decision-maker to a hybrid model in which human expertise is augmented by computational precision.

Speed is another critical dimension where AI is expected to transform dental practice. Tasks that traditionally require significant clinician time such as radiographic analysis, treatment planning, and patient documentation can be partially automated, allowing professionals to focus on higher-level clinical reasoning and patient interaction. This increase in efficiency has implications not only for individual practices but also for broader healthcare systems, where demand often exceeds capacity.

Beyond diagnostics, AI introduces a paradigm shift in treatment planning and predictability. The ability to simulate outcomes, particularly in orthodontics and surgical disciplines, enhances both clinical accuracy and patient communication. Patients are no longer passive recipients of care but active participants who can visualize potential outcomes

before treatment begins. This level of transparency may improve adherence, satisfaction, and overall treatment success.

However, despite these advantages, the integration of AI into dentistry is not without challenges. The current landscape is characterized by a gap between technological capability and real-world implementation. Many AI models perform well in controlled environments but lack validation in diverse clinical settings. This raises concerns about reliability, especially when systems are applied to populations or conditions that differ from the training data.

Another critical issue is the potential overreliance on AI. While these tools are designed to assist, there is a risk that clinicians, particularly less experienced ones may depend excessively on algorithmic outputs. This could lead to a decline in fundamental diagnostic skills over time if not balanced with proper training and critical thinking. Therefore, the incorporation of AI into dentistry must be accompanied by educational strategies that emphasize interpretation, validation, and clinical judgment.

Ethical considerations further complicate the discussion. The lack of transparency in many AI systems, often referred to as the “black box” problem, poses challenges in accountability and trust. Clinicians must be able to justify their decisions, and reliance on opaque algorithms may create legal and ethical uncertainties, particularly in cases of diagnostic error.

Despite these limitations, the trajectory of AI in dentistry is unmistakably forward. As datasets become more robust, algorithms more transparent, and validation more rigorous, AI is expected to transition from an auxiliary tool to an integral component of clinical workflows. Importantly, this transformation will likely create a competitive divide within the profession.

Clinicians who adopt and integrate AI into their practice early will gain a significant advantage in terms of efficiency, diagnostic accuracy, and patient engagement. Conversely, those who resist or delay adoption may find themselves at a disadvantage in an increasingly digital and data-driven healthcare environment. In this sense, AI is not merely a technological advancement, it is a shift in the professional paradigm of dentistry.

5 CONCLUSION

Artificial intelligence is poised to fundamentally reshape dentistry, offering unprecedented improvements in diagnostic accuracy, clinical efficiency, and treatment predictability. Its ability to process complex datasets, standardize interpretations, and support decision-making positions it as one of the most impactful innovations in modern dental practice.

While important challenges remain including issues related to validation, ethics, and integration the potential benefits of AI far outweigh its current limitations. Rather than replacing clinicians, AI enhances their capabilities, enabling a more precise, efficient, and patient-centered approach to care.

The future of dentistry will likely be defined by the synergy between human expertise and artificial intelligence. In this evolving landscape, early adoption and adaptation will be key determinants of professional success. Clinicians who embrace AI will not only improve the quality of care they provide but also position themselves at the forefront of a rapidly transforming field.

Ultimately, artificial intelligence represents not just an incremental improvement, but a paradigm shift one that will redefine how dentistry is practiced, taught, and experienced.

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